**Jet Propulsion Laboratory**
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# Deflection Assessment for a Gravity Tractor Spacecraft

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# Introduction

- Increased focus in recent years regarding threats from asteroid impacts on Earth

- NASA actively researching mitigation techniques for deflection of potentially hazardous asteroid

- Kinetic impactor and gravity tractor are two with most mature technology

- For long lead times, gravity tractor is a viable option

- Desirable to test technique prior to actually using it for a real asteroid threat

# Gravity Tractor

- Spacecraft "hovers" over an asteroid, typically in the asteroid velocity or anti-velocity direction, using ion engines to maintain a constant altitude
  - Thrusters must be canted to avoid plume impingement on asteroid
  - Distance from asteroid must be relatively close (~several hundred m) to maximize gravity pull from spacecraft
- Technique was slated to be a demonstration on Asteroid Redirect Robotic Mission (ARRM)
  - Primary mission was to pick up a 20T boulder from asteroid 2008EV5 for return to Earth vicinity
  - Combined s/c and boulder mass of 20T, with hover in "halo" orbit would have nominally provided acceleration of $5.7 \times 10^{-12}$ m/s$^2$ to asteroid
  - Mission was recently cancelled

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# Gravity Tractor

- Measurement of the deflection accomplished by using spacecraft as a radio beacon, staying in the vicinity of the asteroid for some period of time after gravity tractoring, or by leaving a small radio beacon in orbit after main s/c departs

- Two questions needed to be answered
  - How long does tractoring need to take place to make a measurable deflection?
  - How long does beacon need to remain in asteroid vicinity to measure deflection at a significant level of signal to noise (S/N)?

- This paper tries to answer these questions, using scenario developed for ARRM

# Asteroid Orbit Determination

- Asteroid orbits determined primarily from astrometric image data obtained from ground-based telescopes
  - Observed values are the Right Ascension and Declination of brightness centroid of asteroid (angular measurement)
- Limited number of asteroids also have range data from radar bounces
  - Only practical when asteroid is < 0.1 au from Earth
  - Very powerful data when its available
- Accuracy of orbit dependent on several factors, including data amount, quality, geometry, length of observation span
- Initial orbit estimates provided by Solar System Dynamics group at JPL

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# Spacecraft Orbit Determination

- Spacecraft orbits determined using primarily radiometric tracking data
  - Doppler (measures line-of-sight velocity)
  - Range (measures line-of-sight distance)
  - DDOR (measures angular position of s/c in plane-of-sky)
  - Data obtained using tracking stations located at 3 complexes around the world (Goldstone, CA, Madrid, Spain, Canberra, Australia)
- For s/c in proximity around asteroid, optical images of asteroid (Opnav) from s/c are also used
  - Opnav provides accurate asteroid relative measurement, as opposed to radiometric data, which are tied to Earth

# Orbit Determination

- For both asteroid and s/c, orbits are determined using linearized least squares fit to all the data

- Estimation process produces formal covariance matrix which gives 1 sigma error values for the estimated orbit

- Estimation process also has "consider" parameters
  - These are parameters which are difficult to estimate, so they are not adjusted in the fit, but their errors contribute to the uncertainty in the orbit
  - Turned out to be a significant factor in the ability to detect the signal from gravity tractoring

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# Simultaneous Estimation of Asteroid and Spacecraft

- 1st method – ground-based asteroid solution, with associated covariance, used as a priori for estimating spacecraft state in vicinity of asteroid
  - Asteroid orbit is also corrected in combined solution, but is constrained by a priori covariance
  - Information from ground asteroid observations embedded in the covariance
  - Local solution for asteroid may be good, but does not often yield accurate long term orbit for asteroid
  - This method typically used by mission Navigation Teams for near real-time navigation of spacecraft

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# Simultaneous Estimation of Asteroid and Spacecraft

- 2$^{nd}$ method – spacecraft orbit solution used as "pseudo-range" data
  - Spacecraft orbit solution around asteroid first computed
  - Range from Earth to spacecraft adjusted to center-of-mass of asteroid
  - Resulting pseudo-range to asteroid from Earth data combined with astrometric observations to estimate asteroid orbit
  - Pseudo-range data equivalent to direct ranging measurement to asteroid
  - Advantage of being able to differentially weight and select combinations of astrometric and range data to get better fit
  - Preferred method for determining gravity tractor acceleration

# ARRM Scenario

- Test gravity tractor deflection detection using ARRM scenario
- Baseline ARRM scenario
  - Spacecraft arrival at asteroid 2008EV5 on June 20, 2023
  - Start gravity tractor on December 7, 2023
  - Tractor time variable
  - Depart 2008EV5 on January 21, 2024
- Alternate, "late arrival" scenario
  - Spacecraft arrival at 2008EV5 on March 2, 2024
  - Start gravity tractor on August 25, 2024
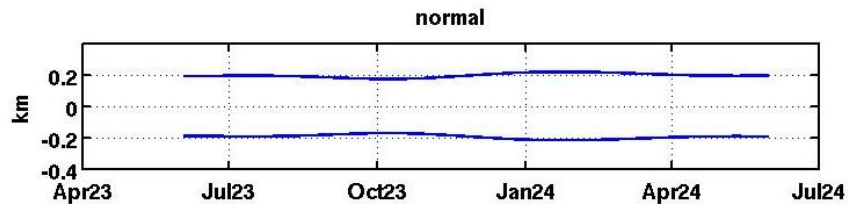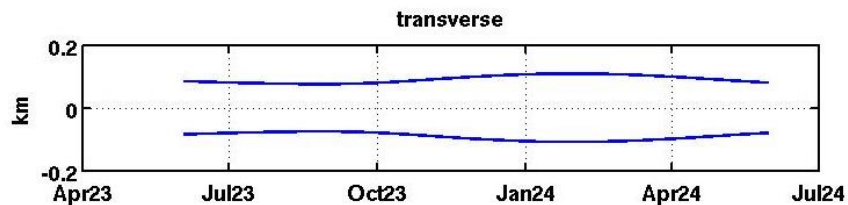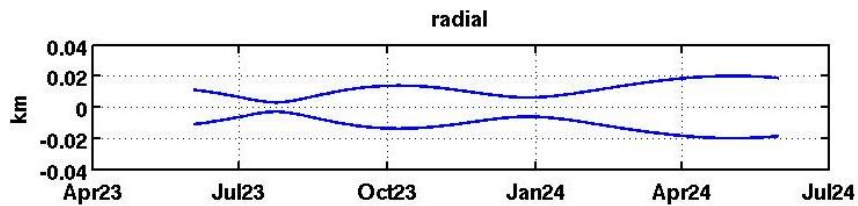  - Depart on September 25, 2024

# Example of Asteroid Uncertainty Using Just Ground Astrometry (2008EV5)
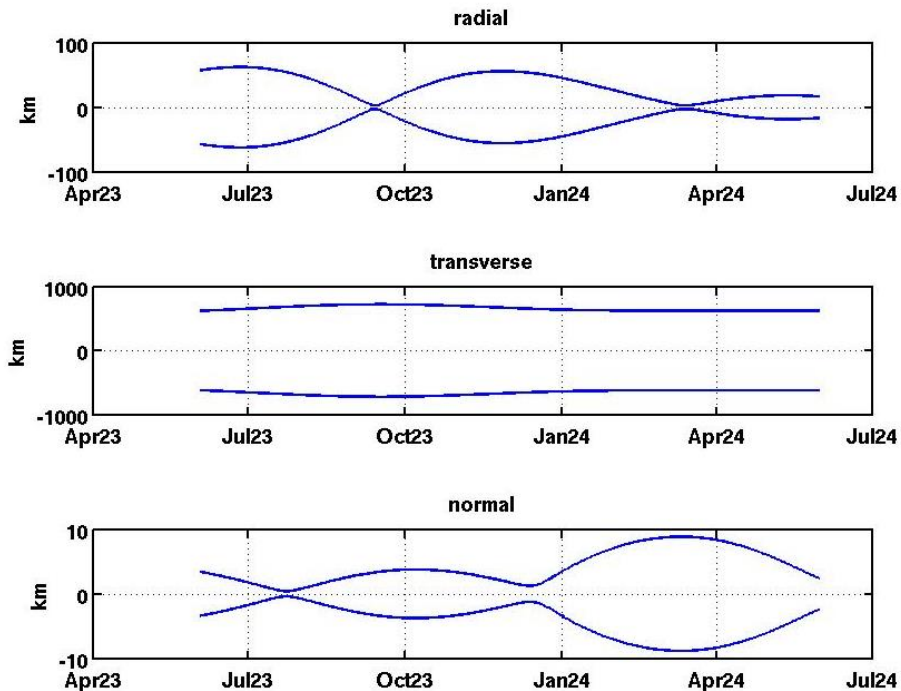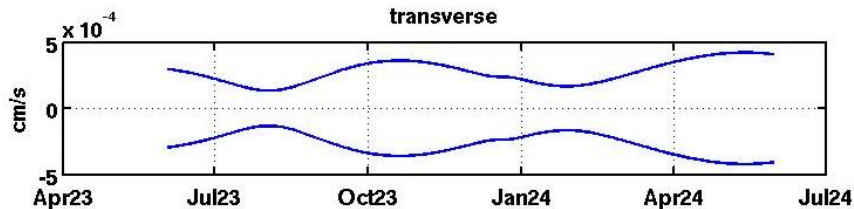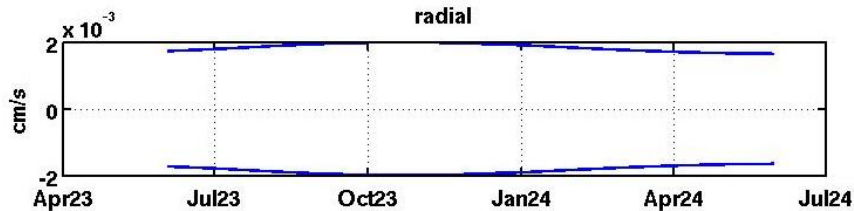


Heliocentric RTN Position
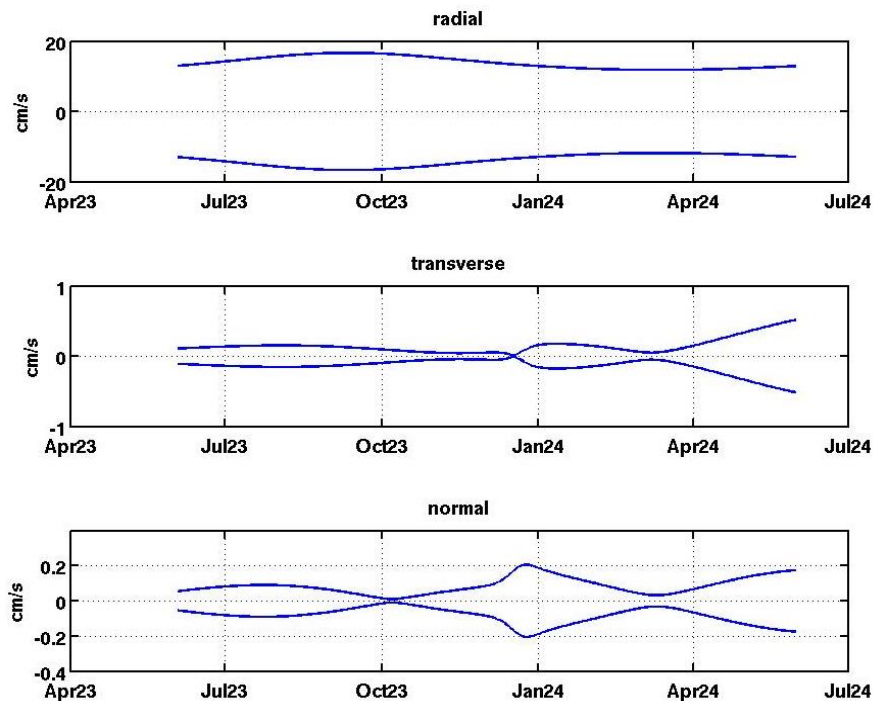
Heliocentric RTN Velocity

# Ephemeris Uncertainty in 2008EV5 After Spacecraft Tracking from June 2023 to November 2023



Heliocentric RTN Position
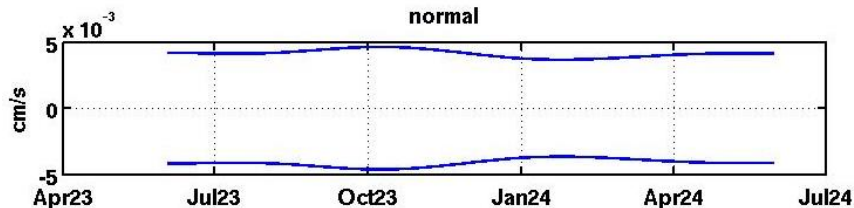
Heliocentric RTN Velocity

# Detecting the Deflection

- In order to detect the amount of deflection, the change in asteroid orbit must be above background uncertainty in asteroid orbit

- Data providing information on deflection are Earth-based measurements of spacecraft in vicinity of asteroid
  - Doppler: measures line-of-sight velocity of spacecraft relative to Earth.  3 sigma accuracy ~ 0.3 mm/s
  - Range: measures line-of-sight range to asteroid, equivalent to direct radar ranging of asteroid: 3 sigma accuracy ~ 6 m
  - Delta-Differential One-way Range (DDOR): angular measure of s/c location in Earth plane-of-sky: 3 sigma accuracy ~20 nrad
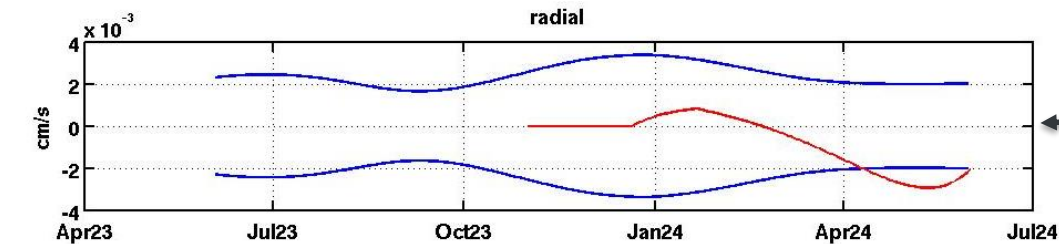
# Position Deflection on 2008EV5 As Seen From Earth
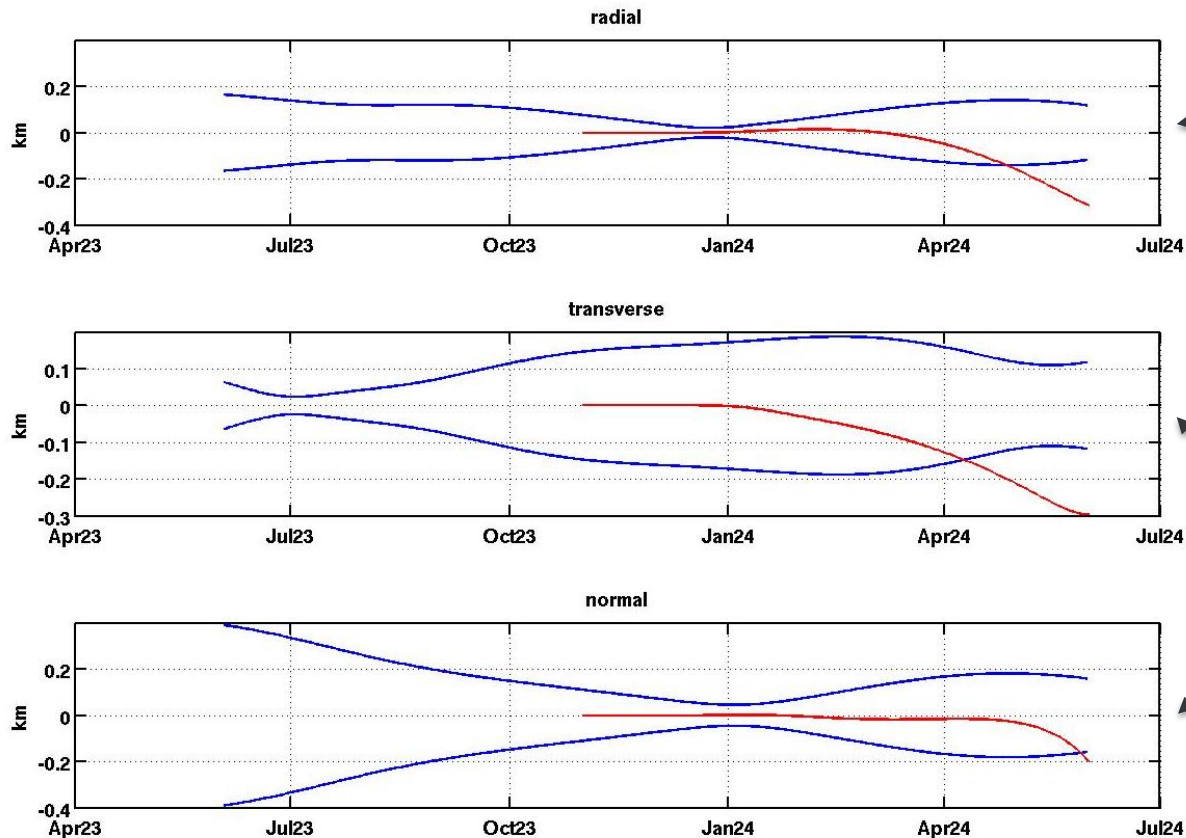


radial

Earth radial direction along range. Deflection well above 5 m

Red line indicates deflection of asteroid due to gravity tractor

transverse

normal

Approximate 3 sigma noise of DDOR measurements, scaled by distance, ranges between 0.3 and 1.8 km. Deflection signal well below this
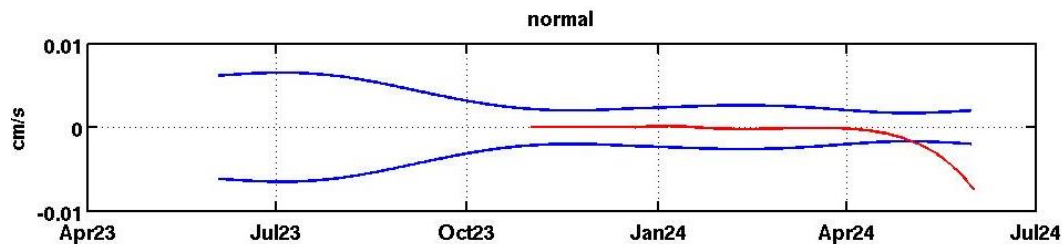
# Velocity Deflection on 2008EV5 As Seen From Earth



Earth radial direction along Doppler direction.
Deflection well below 0.3 mm/s
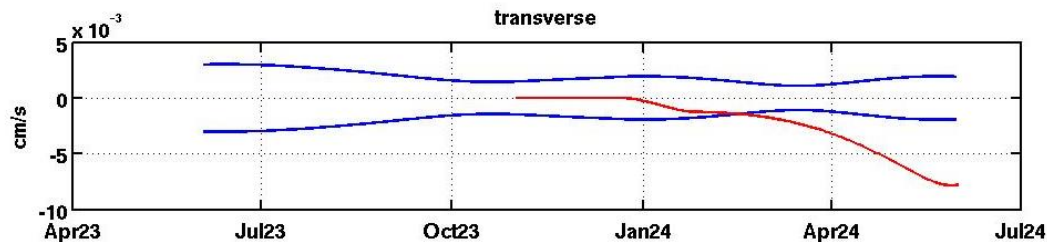
Red line indicates deflection of asteroid due to gravity tractor

# Covariance Study

- For high fidelity, quantitative determination of deflection, full covariance study performed

- Estimated parameters in filter include asteroid state, nominal acceleration from gravity tractor ($5.7 \times 10^{-12}$ m/s$^2$) with 100% a priori uncertainty

- A priori sigma divided by postfit uncertainty on acceleration, measure of S/N
  - Use S/N of 10 as floor to determine if deflection was detected

- Consider parameter with most influence was the Earth-Moon barycenter ephemeris uncertainty
  - Not surprising since Earth is the platform used to measure deflection, so any error in the Earth's location affects how well asteroid orbit can be determined

# Earth Ephemeris Uncertainty

- Formal covariance of Earth ephemeris obtained from B. Folkner (SSD Group at JPL)

- Represents best current fit of Earth ephemeris from astrometric and spacecraft data to date

- Current best estimate (CBE) propagated to future represents knowledge without future observations (conservative case)

- Scaled down value of covariance for future represents presumed improvement with future data

# Results – Sensitivity of Deflection Measurement to Post-tractor Duration
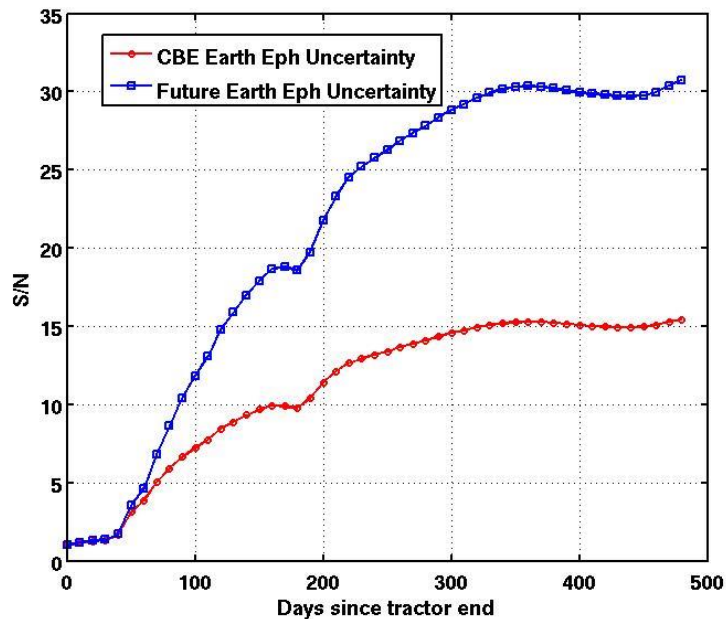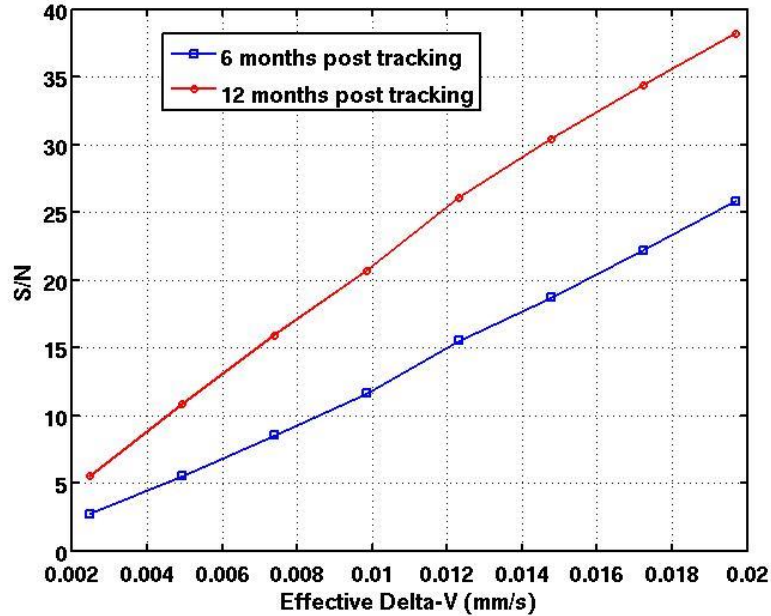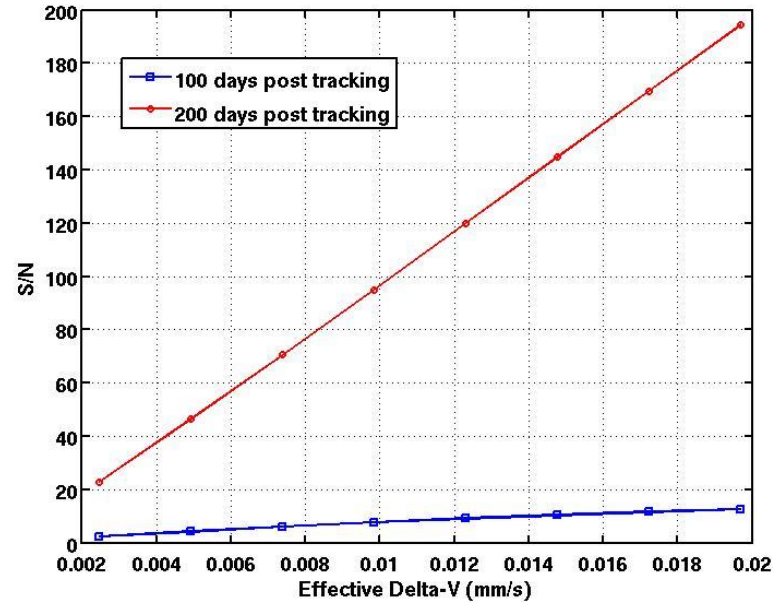


Baseline trajectory
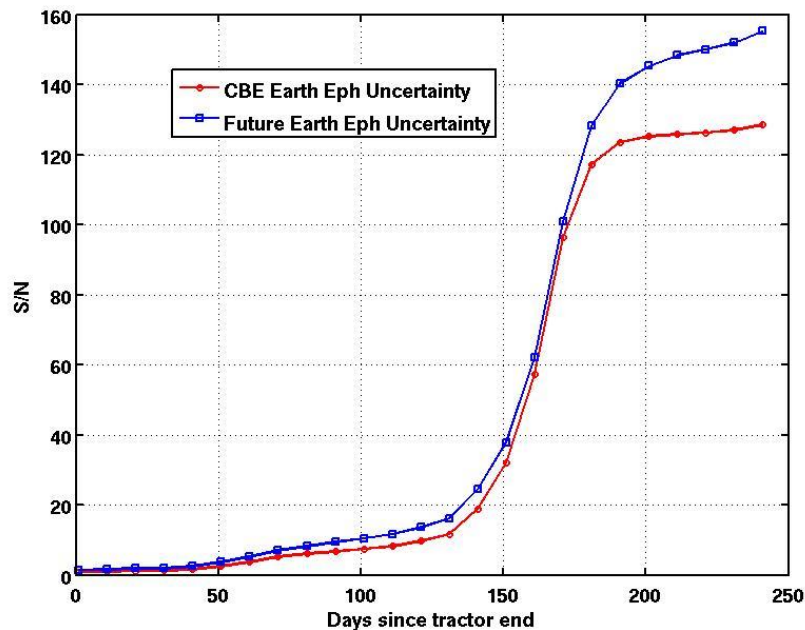
Late arrival trajectory

# Results – Sensitivity of Deflection Measurement to Accumulated Delta-V



Baseline trajectory



Late arrival trajectory

# Summary and Conclusions

- To achieve S/N of 10, minimum of 4-6 months of tracking following deflection is needed

- Even with small imparted delta-v on asteroid (0.05 mm/s), cumulative effect over time on asteroid position, provides enough signal for range data to detect

- Results highly sensitive, however, to:
  - Assumptions on uncertainty in Earth ephemeris
  - Time period of experiment

- Future work
  - Examine cause of sensitivity to time period
  - Examine ability to detect deflection for realistic hazardous asteroid (as opposed to deflection experiment)

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